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GLARE AND AGE: ACQUISITION OF A CLINICAL DATA BASE FOR AIRCREW STANDARDS

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The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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The trend towards a significant age-related decline in contrast sensitivity that we demonstrated in subjects aged 21 to 50 in previous studies prompted a replication with a large sample size and an investigation of scattered light, measured indirectly by disability glare, as a function of age.

1) We were unable to confirm the age-related decline of contrast sensitivity in the age range 21 to 50 with a large sample size, 30, in each decade. Contrast sensitivity to neither externally generated nor interference gratings changed significantly with age.
2) The high spatial frequency cutoff derived from the contrast sensitivity to 12, 16, and 20 cycle per degree gratings did not vary as a function of age. This is consistent with the fact that we selected only those subjects with 20/20 or better visual acuity.
3) Consistent with the lack of declining contrast sensitivity over this age range was the lack of a significant age-related increase in susceptibility to disability glare as measured by sensitivity to 4 and 12 cycles per degree gratings without and with glare. The interaction between age and glare condition was not statistically -

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significant.
4) Increment threshold for a low mesopic background did not change significantly as a function of age.
5) There was a significant increase in the increment threshold limited to the glare condition for the oldest decade in the paradigm simulating night-time glare. The lack of a significant age-related increase in increment threshold directs the attention towards some other explanation than an age-related increase in scattered light for the increase in increment threshold during glare for the oldest decade.

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GLARE AND AGE: ACQUISITION OF A CLINICAL DATA BASE FOR AIRCREW STANDARDS

INTRODUCTION

Normal subjects over the age of 50 have significant decreases in high spatial frequency contrast sensitivity compared to those under the age of 50 (1,2,3,4,5). We demonstrated significant age-related decreases in binocular high spatial frequency contrast sensitivity in ophthalmologically normal 20- to 40-year-olds (6). Thus, there may be gradual loss of contrast sensitivity from age 20 to 50 even with subjects (Ss) selected for visual acuity of 20/20 or better. Visual acuity decreases with age in Ss without ocular disease, if they are not selected for visual acuity (3). Some investigators (7,8) believe that changes in the visual neural system partially account for the loss of visual acuity and high spatial frequency contrast sensitivity with age. In fact, 2 recent studies have shown loss and disruption of photoreceptors (9,10) with age. This is difficult to interpret due to fixation artifacts and three-fold variability in foveal photoreceptor counts across normal young Ss. However, Ordy et al. (12) have demonstrated a direct relation between rhesus foveal photoreceptor loss and decreased visual acuity with age. There are also decreases in the number of ganglion cells (13), in optic nerve fibers (14,15), in the number of neurons in the striate cortex with age (a decrease from 46 to 24 million/gram wt from ages 20-80 (16,17)), and a loss of apical and basal dendrites (18) in the motor cortex.

It has also been suggested that increased density and light scattering by the crystalline lens can account for the changes in contrast sensitivity and visual acuity with aging (3,19,20). Hemenger (20) showed that narrow angle light scatter could explain the loss of contrast sensitivity with aging and yet did not think there was sufficient empirical evidence to support it. In middle-aged subjects, about 10% of the light arriving at the cornea is scattered outside of the geometric retinal image. Most of this occurs as narrow angle scattering. The cornea, the lens, and the retina contribute about equally to light scatter in the eye in young subjects (21). Among these, the scattering properties of the lens have been pursued the most vigorously probably because of the dramatic nature of the restoration of vision following removal of cataracts, most of whose perceived effect on light is to scatter it.

Several age-related changes of the lens could result in degradation of the retinal image. Part of the increase in light scatter with age is due to increase in fluorescence of the lens. However, even at age 60, the ratio between the luminance of the sky and the lens fluorescence it produces is only .017, which would be just above the threshold for detection (22). It becomes significant (.121) only at age 80. Trokel (23) showed that, in a slit lamp image, absorption of light as a function of age accounts for only a small fraction of the decreased transparency (24). Most of the effect of

aging on degradation of the image is through spectrally selective absorption in the lens. This brunescence of the lens combined with senile miosis, which reduce retinal illumination by a factor of 3 between the ages of 20 and 60, may be sufficient to account for decreased contrast sensitivity with age (3). This was concluded because of the loss in contrast sensitivity of young subjects when viewing through .5 OD filters. However, the effect of the resultant larger pupil size with increased spherical aberration was not studied. When it was studied (25), simultaneous constriction and appropriate filter density to simulate retinal illuminance and pupil effects of the old in young observers, had no effect on contrast sensitivity of young observers. In the middle-aged category (21 to 50), these effects would be expected to be minimal. The loss in contrast sensitivity with age is greater than can be accounted for by the decrease in retinal illuminance due to brunescence and senile miosis (20).

The increases in high molecular weight protein aggregates and a corresponding loss of low molecular weight proteins with aging cause increased light scattering. Small particles cause more backscatter, and large ones cause proportionally more forward scatter (2,20). The age-related backscatter, the increased absorption, and fluorescence mainly occur in the nucleus of the lens.

In 85 Ss with 20/20 vision and normal media, backscatter increased with age (19). There was good correlation between the brightness of the backscatter seen with a slit lamp and glare susceptibility as a function of aging. One might think then, that the lens contributes greatly to the increase of susceptibility to glare (and therefore forward light scatter) as a function of age. If this is true, the lens might also be the major contributor to the decrease in visual acuity and contrast sensitivity which has been demonstrated as a function of age. Allen and Vos (26) did not find a direct relation between contrast sensitivity and light scatter in the anterior media. Weale (27) found that the resolving power of lenses from cadavers remained invariant with age. The ocular media can produce large amounts of backscatter before there is a remarkable effect on acuity (19,24). Part of the reason for this may be that visual acuity is not a good measure of the effects of light scattering since relative decrease in spatial frequency resolution due to light scattering is less than the relative loss in contrast sensitivity (28,29). Also, backscatter and forward scatter are not necessarily tightly coupled (20). Part of the reason for the lack of very good correlation between light backscatter and visual acuity might also be because the amount of backscattering depends on the polarization of the light. The backscatter can be decreased dramatically by altering the polarization of the entering light (30). It could also be that either the right scattering medium is not being studied or that scattering is not the only or major culprit.

The decrease in average pupil diameter with age is another optical parameter which potentially affects the retinal image by decreasing retinal illuminance. However, the changes, especially in the 21- to 50-year age group with photopic adaptation, are too small to account for the decrease in contrast sensitivity demonstrated over this age range. The backscattering of light by the cornea and lens accelerates at about age 40 (31). Human corneal thickness increases with age, but thickness was not the source of increased scatter since subjects equated for corneal thickness still had increased light scatter with age (31).

The vitreous and vitreoretinal interface also change with age and could produce significant forward narrow angle light scattering (32) due to large particles. Although the retina is a major contributor to light scatter in the eye, there have been no studies attempting to determine the role of the aging retina and vitreoretinal interface in increased scatter and decreased sensitivity to high spatial frequencies in the aging eye.

The evidence for the role of age-related increase in light scatter in decreased contrast sensitivity is conflicting. Some studies minimize the role of light scattering as the major contributor to decreased high spatial frequency sensitivity in older subjects without clinically observable media opacities. Owsley et al. (33), showed that patients with pseudophakia who lack one of the important light scattering and light filtering media in the eye had normal (i.e., lower than that for younger subjects) contrast sensitivity for their age. However, there remained the possibility that scattering by the cornea, vitreous, vitreoretinal interface, or retina accounted for the difference with aging. Dressler and Rassow (34) studied contrast sensitivity of 95 subjects 12 to 71 years old with laser interference fringes and found that the 95% confidence interval for contrast sensitivity was 0.5 log units (no larger than the standard deviations of a group from 21 to 40 years old), implying a low likelihood of significant change of laser interference fringe contrast sensitivity with age. Morrison and McGrath (2) studied 45 subjects from 15 to 80 years old with no clinical opacities in any but 6 of the older subjects. They stratified the age groups and found that the decrease in laser interference fringe contrast sensitivity with aging was the same as the decrease in contrast sensitivity determined with conventional gratings. The ratio between contrast sensitivity measured by the 2 techniques remained constant with age implying that the optical quality of the eyes remained constant as a function of age.

The purpose of the present study is to test the hypothesis that there is an age-related increase in light scatter in subjects without clinically detectable media changes which could account for the loss in contrast sensitivity to high spatial frequency in the age range 21-50 years. Relative light scatter will be estimated indirectly by the effects of glare on contrast sensitivity and by the relation between contrast sensitivity determined by interferometry and by externally presented gratings. If decrease

in contrast sensitivity is due to subclinical age-related increase in light scatter, the practical implications for Air Force personnel who must depend on vision during glare exposure would be different from those if decreased contrast sensitivity were due to neural factors.

It is known that glare testing can reveal light scattering not detected by visual acuity or contrast sensitivity testing alone (29,35,36,37). The addition of a glare light potentiates the effect of a scattering source in the media (38,39). If the light scattering is great enough so that it is just at the threshold of detection with contrast sensitivity, as is postulated with aging, it should be easily detectable with the use of a glare source.

Only a narrow range of probe stimulus spatial frequencies have been examined in previous studies of disability glare and aging. We intend to re-examine the sensitivity to glare as a function of age using contrast sensitivity as a measure and using test stimuli with different spatial frequency content and assessing sensitivity at 2 different background light levels in 21 to 50-year-old subjects without ocular pathology.

We will also examine the relative contributions of neural vs. media aging to possible age-related decreases in contrast sensitivity using a measure of contrast sensitivity, laser interferometry, which is less sensitive to the image degradation produced by age-related media changes.

MATERIALS AND METHODS

Subjects

There were 90 subjects in the age range 21 to 50 years with 30 subjects in each decade. They were recruited from The University of Texas Health Science Center at San Antonio (UTHSCSA) faculty students, and staff. The subjects were paid $25.00 for participation in the study following completion of all tests.

Inclusion criteria were as follows:

Medical History	No history of eye disease. No history of contact lens use.
Eye Exam	Must undergo complete eye exam and have:
	1) Normal visual acuity (20/20 or better) with spherical equivalent between -5 and +2 D.
	2) Normal confrontation visual fields.

3) Normal motility (no tropias in the cover test).

4) Normal anterior chamber (cornea, lens, angle) - slit lamp.

5) Normal fundus, disc, macula, and vessels - indirect ophthalmoscope.

6) Normal intraocular pressure (less than 22 mm Hg) - applanation tonometry.

7) Normal color vision - D15.

Apparatus

Glare susceptibility was measured monocularly using 2 different types of contrast threshold tests: contrast sensitivity and increment threshold.

Contrast Sensitivity Apparatus

The contrast sensitivity to gratings was measured using the apparatus and techniques previously described (6). The target was a 1.5° circular area of the cathode ray tube (CRT) screen defined by a black Plexiglas tube connected to a black Plexiglas holder for the surrounding fluorescent glare source (Fig. 1). The Plexiglas tube length was .037 m, and the tube extended out perpendicular to the Tektronix 608 XY monitor screen and was positioned approximately centered on the screen. The holder surrounded the fluorescent lamp except for the side facing the subject. On this side, there was a thin (.003 m), clear double Plexiglas cover into which filters could be inserted. This cover was set off .01 m from the holder and about .015 m from the lamp and was flush with the front surface of the center Plexiglas tube to allow the lamp to cool. Black poster board was inserted behind the Plexiglas and inside the Plexiglas tube to prevent light from the fluorescent lamp leaking onto the CRT. The lampholder was surrounded by a black posterboard surround (.25 X .28 m) to prevent leakage back to the screen from the gap between the holder and the cover. The fluorescent lamp (Stocker and Yale 973-510 Circle 9 cool white) was bent into a circle in such a way that the ends with connectors were parallel to each other. The width of the cylinder forming the lamp was .013 m. The outside diameter of the circular lamp was .0828 m and the inside diameter was .0572 m. The straight portion where the ends were bent parallel to each other and normal to the circle was .0253 m in length from the point of bending.

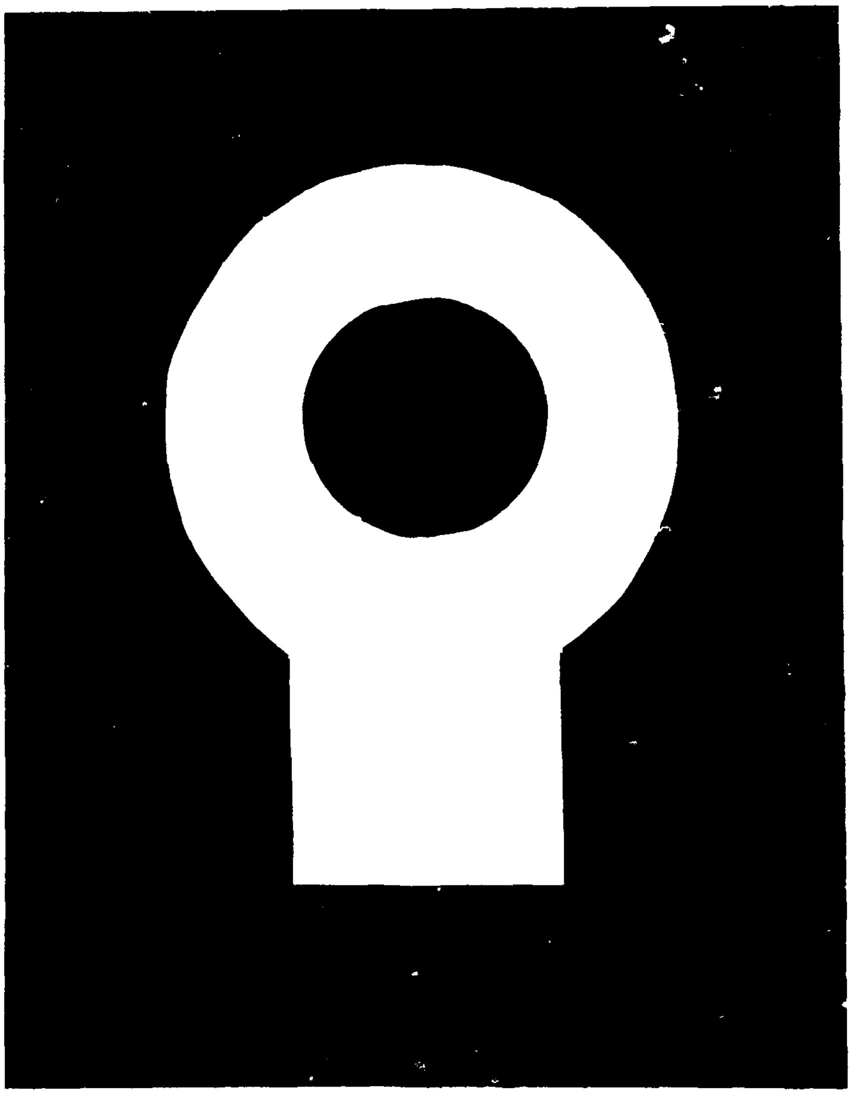

Figure 1. This is a photocopy of a digitized image of a photograph of the grating target (1.5° in diameter) and the surrounding secondary glare source. The fluorescent lamp was positioned in the white keyhole-shaped diffuser around the grating target.

The radiant exposure produced by the fluorescent tube at the position of the eye was measured with the IL 1700 radiometer (4130 J/m^2) and was found not to exceed the MPE with dilated pupils and with the tube at maximum current and unattenuated. The current through the tube (Mercron RL 06-16-1) was adjustable but was kept at maximum. Luminance was regulated to within $\pm 1\%$ by a photo-resistor in the lamp holder aimed at the surface of the lamp. The driving frequency of the lamp was 55 kHz. The tube was allowed to warm up for about 10 min prior to calibration or testing. The room lighting was controlled by dimming a 150-W incandescent bulb in a diffusing fixture. The luminance of the wall to the right of the apparatus was set to 2.74 cd/m^2 using a Minolta spot photometer. The resulting luminance was about 1.71 cd/m^2 surrounding the screen. The fluorescent light increased the ambient lighting to 4.1 cd/m^2 on the wall and 6.85 cd/m^2 on the white poster board surrounding the target. The incandescent light was on and set to the same brightness with and without glare.

Increment Threshold Apparatus

The other instrument for measuring glare susceptibility was developed by Raymond A. Applegate (35). It consisted of a 2-channel tachistoscope (Scientific Prototype N9000) which produced a $.5^{\circ}$ circular test stimulus (TS) flashing at 2 Hz and centered on a 5° square adaptation light (AL) background superimposed on the TS by reflection off a partial mirror through which the TS was viewed (Fig. 2). Both stimulus sources were current-regulated fluorescent lamps. A grain of rice bulb (Cir-Kit Concepts) at 1° nasal to the flashing TS was used as a glare source. The apertures for both TS and AL were .57 m from the eye. The AL was set to .377 cd/m^2 using a Wratten OD 3.0. The luminance of the center of the AL field was measured with a Spectra Pritchard 1980 A photometer (OD1, with a 6 min aperture).

The TS intensity was controlled in 2 ways: Wratten gelatin OD filters inserted just in front of the TS or adjustment of a precision 10 turn potentiometer controlling the current through the fluorescent TS source. This potentiometer was linked by a flexible coupling to another 10 turn potentiometer in a frame attached to the apparatus. A regulated +5 V from the computer (Standard Brands 10 MHz super XT, IBM XT compatible) was led across the arm of the potentiometer through a 470 ohm current-limiting resistor. The wiper and the ground side of the potentiometer were led to the differential input of a 12 bit analog to digital (A-D) converter (Metrabyte Dash 8 with a slew rate of 50,000 samples/s) in the computer.

Laser Interferometry

Contrast sensitivity was also measured using Randwal LIA instrument. Interference gratings produced by a helium neon laser were projected onto the retina through a Maxwellian view system. The intensity level chosen was equivalent to 7.4 cd/m^2 viewed

externally with a 2.5 mm pupil. The target diameter was 2°. The room was dimly illuminated at around 2.4 cd/m², although there were small areas with specular reflections at 24 cd/m².

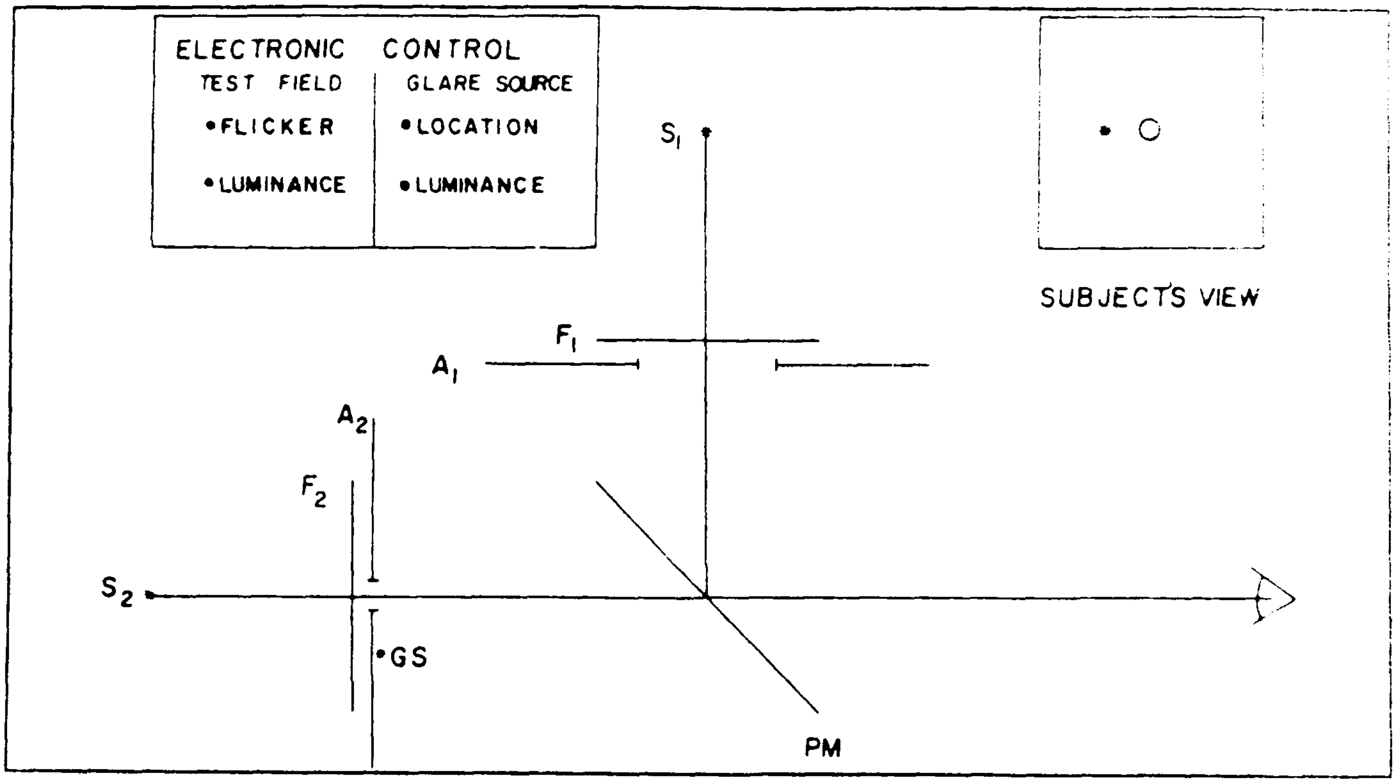

FIGURE FROM APPLEGATE, ET AL., 1987

Figure 2. This is a schematic diagram of the increment threshold apparatus as seen from above. S1 and S2 were current regulated fluorescent tubes. F1 was a 3.0 OD filter. F2 was a set of 7 apertures covered by neutral density filters in incremental 0.5 OD steps each of which could be positioned in front of the source. A1 and A2 were apertures limiting the adaptation and stimulus to 5° and 1° fields, respectively. GS was the small incandescent glare source embedded in the surround around the stimulus. The Ss' view of the display is seen in the inset at the upper right. PM was a partial mirror used as a beam splitter to superimpose the AL and TS. Figure from Applegate et al. (35)

The method of generating the gratings was described in detail by Smith et al. (40). Control of contrast is achieved in the following manner. The laser beam is split into 2 channels with inversely varying intensities by a circular polarizer followed by a calcite crystal beam splitter. One channel is passed through a holographic grating to produce the 2 diverging wavefronts that produce the interference grating. These wavefronts travel exactly the same path, and therefore mechanical disturbances and vibration will affect both equally and will not perturb the resulting interference grating. The other channel passes through a rotating ground glass to remove its coherence and is then recombined with the beam that has passed through the holographic grating. The angle of the polarizer determines the ratio of the intensities of the 2 beams, but the total energy throughput remains constant. Therefore, the contrast of the interference grating varies as the ratio of the intensities of the 2 beams. A 10X eyepiece focuses the fringe field and forms 2 coherent point sources near the nodal point of the eye.

TECHNIQUE

Calibration

Calibrations of the grating and the increment threshold apparatus were carried out on each day of experimentation.

CRT

The CRT was calibrated by measuring the luminances of the peak and trough of 1 cycle at the center of the grating set to 2 cycles per degree (cpd) at 2 m. The measures were made with the overhead incandescent lamp on. A steady grating, at a set contrast, was displayed on the CRT screen by entering digital values to the digital to analog (D-A) converter. Seven values from -1500 to -2048, giving contrasts from about .038 to .005, were used. The screen was also calibrated with the fluorescent glare light turned on. The relation between contrast and voltage from the D-A converter was linear. The coefficients from the linear regression were entered in the data collection program to convert from voltage to contrast. The coefficients with and without the glare source were used during the respective testing sessions.

Fluorescent Glare Source

The fluorescent glare source was also calibrated on each day of testing by measuring the luminance at center left, top, and right with the Pritchard. The lamp was allowed to warm up at least 10 min prior to calibration or testing. The luminance of the glare

source ranged from 14,730 to 16,790 cd/m^2, which produced an illuminance of 13.7 lux at the position of the eye.

Incandescent Glare Source

The current through the glare source in the increment threshold apparatus was adjusted to about .0311 A to produce an illumination of .22 lux at the plane of the subjects' pupil measured centered in this plane with the IL 1700 meter with an illuminance head (SED038 #1658 diffuser W#4218). The lamp was allowed to warm up for 10 min prior to calibration or testing.

Increment Threshold TS Source

Calibration of the TS in the increment threshold apparatus consisted in manually entering into a file the luminance of the TS and automatically entering the digitized value (100-4096) associated with each of 10 revolutions of the potentiometer. This was done by a semiautomatic program which also carried out a linear regression on the digital value-luminance readings. The luminance of the center of the TS was measured with the Pritchard photometer (OD 1 with a 6-min aperture). The digital value was the average of 10 samples collected with the Dash 16 A-D converter in a 40-ms interval. The linear regression provided an adequate estimate of the relation between luminance and digital value. The coefficients of this regression were stored in a file and were used by the main testing program to convert from digital value to luminance at threshold. A debounced pulse produced by a button press triggered the AD board to collect data.

Laser Interferometer

The polarizer was set under computer control to give 50% contrast. If the instrument were functioning properly, then the intensity in the 2 channels would be equal. This was tested and found to be true by measuring the illuminance produced by the focused spots at the output and alternately occluding one of the channels.

Procedure

Except for interferometry, testing was always done on a day following the eye exam. Only the right eye of each subject was tested. Preceding the final testing, the subject had undergone preliminary instruction and was given exposure to the testing paradigm, so they were already familiar with the procedure and thus would not exhibit so strong a practice effect as if they had never experienced the test. They were again instructed to perform the task. The subject was fitted with a trial frame and the correction to be used in the first test. This manifest refraction was

available from the eye exam record. The subjects were corrected for the test distance which in the case of the increment threshold test was .57 m and 2 m for the contrast sensitivity test. The lenses were always inspected and cleaned thoroughly before use. The subjects were quizzed about the appearance of the glare effects and if they could be minimized by slight changes in the position of the lens by pressing on the frame with the finger. If so, this position was used during the test.

Testing was carried out in 2 or 3 sessions on separate days depending on the subjects' time constraints. The order of the 3 types of test was varied semirandomly, but sensitivity without and with glare for both tests was measured on the same day, and generally, sensitivity without glare was measured before the corresponding sensitivity with glare. When sensitivity with glare was measured before sensitivity without glare, the subject was allowed to adapt to ambient illumination for 10 min or until they reported the presence of no afterimages due to the glare source, whichever was longer.

Increment Threshold Without Glare

The subject was aligned with the apparatus, and the pupil plane was kept fixed with a chin-forehead rest. The eye was aligned with the stimulus fields by moving the headholder until the square AL field appeared centered in the square aperture in a piece of black velvet in front of the AL field. The room lights were turned off. The potentiometer controlling TS intensity was set to mid-range and the filter (1 of 7 in .5 OD steps from 1.1 to 4.1) in front of the TS source was adjusted by the experimenter by verbal feedback from the subject to a value at which the subject barely saw the flashing TS.

The testing program stored on the computer hard disk was recalled and subject information and the AL intensity and the TS filter value previously determined were entered. There were 10 determinations of threshold using the method of descending limits. Threshold was determined in the following manner. The TS intensity was always controlled by the experimenter with feedback from the subject. The TS was set at an easily visible level then its intensity was decreased by turning the 2 coupled 10-turn potentiometers. The subject was providing feedback saying "see it" frequently as long as the TS was visible. Near-threshold responses were slower and less certain and the potentiometer controlling TS intensity was turned with smaller increments and more slowly until the subject reported "don't see it." The experimenter pressed a button at this point initiating a data collection routine by the A-D board. The threshold value recorded at this point was the average of 10 digitizations during a 40-ms period. The digital value was converted into luminance and into the Weber fraction ($\Delta I/I$) automatically by the computer taking into consideration the TS filter and the AL luminance. Descending thresholds were repeated 10 times. The computer program rejected the highest and

lowest threshold values and averaged the 8 remaining values and also provided the standard deviations of the luminance at threshold and $\Delta I/I$. After each data collection, the subject was asked if he/she was certain of the setting. If the subject was sure, then the same button was pressed a second time, thus storing the data on disk. If the subject changed the threshold decision, a second button was pressed. This rejected those data and allowed a new collection to be initiated by pressing the first button. The incandescent glare source was turned on and allowed to warm up before the next test.

Increment Threshold With Glare

The optical correction was again changed to that appropriate for the distance. The subjects were instructed to maintain the same criterion as in the previous test,not to look at the 1^{o} nasal glare source directly, and to note any very bad glare beams through the TS. If such beams were present, we attempted to determine if this could be due to positioning of the lens relative to the eye and if this could be minimized by pressure on the trial frames or lens bottom by the subject.

Contrast Sensitivity Without Glare

Contrast sensitivity was determined using the method of ascending limits (or increasing contrasts). The technique and instructions were the same as in the previous report (6) except that contrast sensitivities for gratings of only 4 spatial frequencies, 4, 12, 16, and 20 cpd, were determined. We measured the sensitivity to 12, 16, and 20 cpd because they were all on the linear portion of the high spatial frequency cutoff of the data in the first 2 studies (5,6). They were also the spatial frequencies which differed the most with age in the previous studies. These 3 contrast sensitivity data points allowed us to carry out a linear extrapolation to the high frequency cutoff. Contrast sensitivity to 4 cpd was measured because it was found to change significantly with age in our second study of monocular contrast sensitivity (5) and because, in the pilot study carried out last year, there was a significant interaction between glare effect and spatial frequency with a greater effect on the lower spatial frequency. We wanted to test the hypothesis that the glare would have more effect on contrast sensitivity to low than to high spatial frequencies with a larger sample size.

Another difference from the previous testing procedure was that the point of departure of contrast increase in the increasing contrast method was elevated to a level just below previously demonstrated average threshold for spatial frequencies 16 cpd and greater to avoid the long wait while the automated testing paradigm changed the contrast from 0 to over half the contrast range at a very slow rate.

The subject's head was aligned and fixed in position so that the visual axis of the right eye was normal to the CRT screen using a chin-head rest fixed to an adjustable slit lamp table. The correction in the trial frames was changed to the appropriate correction for the distance (2 m).

Contrast Sensitivity With Glare

Again, the subject was instructed to maintain the same criterion not to look at the glare source and to minimize any large glare effects due to the lenses themselves. During glare, contrast sensitivities to only 4 and 12 cpd were measured. This reduced exposure to the bright glare source and reduced the time of the experiment so that the subjects did not become fatigued and still gave information about the effects of glare on high and middle spatial frequencies.

Laser Interferometry

The subject sat in front of the instrument with the chin and head fixed on a chin-head rest whose position could be varied vertically. The room was kept dimly lit. The eye was illuminated by 2 infrared light-emitting diodes (LEDs) embedded in the eyepiece. The interferometer could be moved on a sliding x-y table to position the focused coherent beams in the pupil by viewing the 10X magnified image of the eye and the infrared LEDs transmitted to a TV monitor by a charge-coupled device (CCD) camera coaxial with the eye piece. When the edge of the pupil was in focus and its horizontal diameter aligned between the 2 LEDs, the positioning was correct. The left, untested eye, was covered with a white eye patch. We also measured the pupil diameter from the screen of the monitor.

The interference grating was presented in a temporal ramp to avoid transients for a duration of .25 s. The duration of the blank was also .25 s and was presented randomly interspersed with the other contrasts. The contrast was varied, under computer control with feedback from the Ss' responses, by changing the position of the polarizer with a stepper motor. The spatial frequency was varied, under computer control, by changing the position of the holographic grating relative to the expanded focused laser beam by means of a stepper motor and worm gear assembly.

The Ss were first given a short training session to familiarize them with the procedures. Threshold was determined by presenting a descending series of contrasts to the S. Trials were marked by beeps. When the S failed to signal presence of the target on 2 successive trials, threshold was taken as the contrast of the target on the last stimulus detected. Threshold was determined for each of the 3 spatial frequencies. The session was repeated, if the S did not have a clear understanding of the procedure.

In the testing session, a "seed" threshold contrast to be used in the constant stimulus method was determined on 3 descending contrast passes preceding determination of threshold with the 2 alternative temporal forced choice constant stimulus method. If the threshold so determined agreed within 3 dB on the last 2 passes, then this value was chosen as the "seed" in the constant stimulus method. The passes continued until there was agreement on 2 successive passes.

Contrast sensitivity to 16, 20, and 30 cpd was measured in that order with the presentation of 55 trials with 5 catch trials for each spatial frequency. In the constant stimulus method, the 5 contrasts at 3 dB steps were chosen to straddle the "seed" contrast. There were 10 trials for each of 5 contrasts covering a 15 dB range (a factor of 5.6) distributed equally on both sides of the threshold previously determined using a rapid staircase procedure.

The subjects signaled detection of the target by a button press which was recorded by the computer along with the contrast on that trial. The psychometric curve was fit by a linear regression, and the interpolated contrast giving 60% detection was chose as threshold by the computer program.

RESULTS

Data Analysis

The nonglare/glare contrast sensitivity data were analyzed by a 3 factor analysis of variance (ANOVA) with 2 repeated measure factors (glare condition and spatial frequency) and one between group factor (age). Statistical software from StatSoft (CSS) running on an IBM-compatible microcomputer (Compaq Deskpro) was used to analyze the results. The ANOVA program was tested on a textbook example (41) of a design identical to the one used here. The results of the tests in the textbook and in the output of the program were the same. The CSS program automatically chooses the correct error terms to test main effects and interactions.

The increment threshold data were analyzed by a 2 factor repeated measures ANOVA with 1 repeated measure, increment threshold, and 1 between groups factor,age. The contrast sensitivities determined with the laser interferometer and the externally presented gratings were analyzed by a 2 factor repeated measures ANOVA with 1 between groups factor, age, and 1 repeated measure factor, spatial frequency. The extrapolated high spatial frequency cutoffs, based on interferometry and on contrast sensitivity to the externally presented gratings, were calculated for each person. These data were analyzed by a one-way ANOVA with 1 factor, age. In addition, the pupil diameters were compared across age groups using a 1 factor (age) between groups ANOVA.

Contrast Sensitivity to External Gratings Without Glare

Contrast sensitivity (across spatial frequency) did not vary significantly with age ($F = 1.22$, $p = .299$). The interaction between age and spatial frequency was also not significant ($F = .698$, $p = .65$). This means that contrast sensitivity was equally invariant with age for all spatial frequencies tested (4, 12, 16, and 20 cpd). The mean contrast sensitivities for each spatial frequency by age group were as follows:

Age group I (21-30) 61, 58, 30, and 25 for 4, 12, 16, and 20 cpd, respectively;
Age group II (31-40) 59, 61, 31, and 27
Age group III (41-50) 55, 55, 29, and 23

Because of the lack of a significant age or interaction effect, we were not statistically justified in examining planned comparisons for individual ages or spatial frequencies. This convention avoids significant results due to chance when there are multiple tests.

There was a significant effect of spatial frequency ($F = 247$, $p < .00001$). The average contrast sensitivities for each spatial frequency across age groups were: 59, 57, 30, and 25. The regression of the logarithm of contrast sensitivity against spatial/frequency for 12, 16, and 20 cpd yielded an extrapolated high spatial frequency cutoff (spatial frequency at log contrast sensitivity = 0) of 50 cpd. The regression was $Y = 2.27 -(.045X)$ with $r^2 = .91$ where X = spatial frequency and Y = log contrast sensitivity. In Figure 3, the linear regression of the contrast sensitivities to 12, 16, and 20 cpd are extrapolated to the axes for each age group. Figures 3 to 6 indicate 1 standard error of mean in a positive direction. If it is not visible, it is less than the size of the symbol.

Contrast Sensitivity to Interference Gratings

Contrast sensitivity to interference gratings did not vary significantly with age ($F = .32$, $p = .732$). The interaction between age and spatial frequency was not statistically significant ($F = .91$, $p = .46$). This means that contrast sensitivity to the interference gratings was equally invariant with age for all spatial frequencies tested (16, 20, and 30 cpd). The mean contrast sensitivities for each spatial frequency by age group were as follows:

Age Group I 46, 33, and 15 for 16, 20, and 30 cpd, respectively
Age Group II 44, 31, and 16
Age Group III 42, 33, and 15

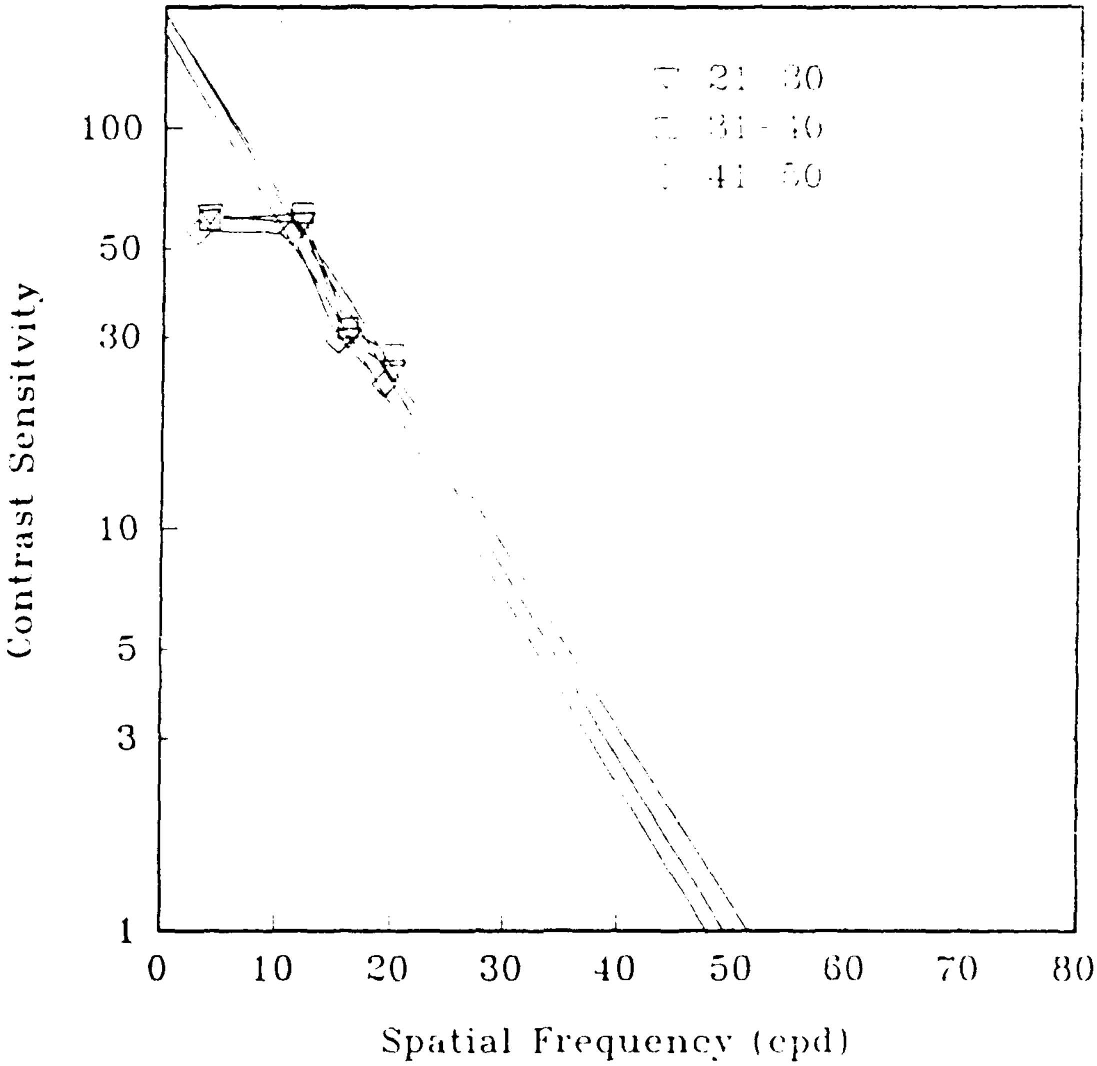

Figure 3. Contrast sensitivity (+1 sem) as a function of spatial frequency of the gratings presented on a CRT plotted log-linearly. The linear regressions for each of the 3 age groups are extrapolated to the axes. The X intercept gives the high spatial frequency cutoff. Note that these cutoffs based on the average contrast sensitivity will differ from the average cutoffs given in the section "Extrapolated High Spatial Frequency Cutoff."

Because of a lack of a significant age or age-spatial frequency interaction, we were not justified in examining planned comparisons of individual age groups or spatial frequencies and age groups.

There was a significant effect of spatial frequency ($F = 309$, $p < .00001$). The average contrast sensitivities across age groups for the 3 spatial frequencies (16, 20,and 30 cpd) were: 44, 32, and 15. The regression of the logarithm of contrast sensitivity against spatial frequency yielded a high spatial frequency cutoff of 66 cpd. The regression was:$Y = 2.17 - (.033\ X)$ with $r^2 = 1$ where Y = log contrast sensitivity and X = spatial frequency (Fig. 4).

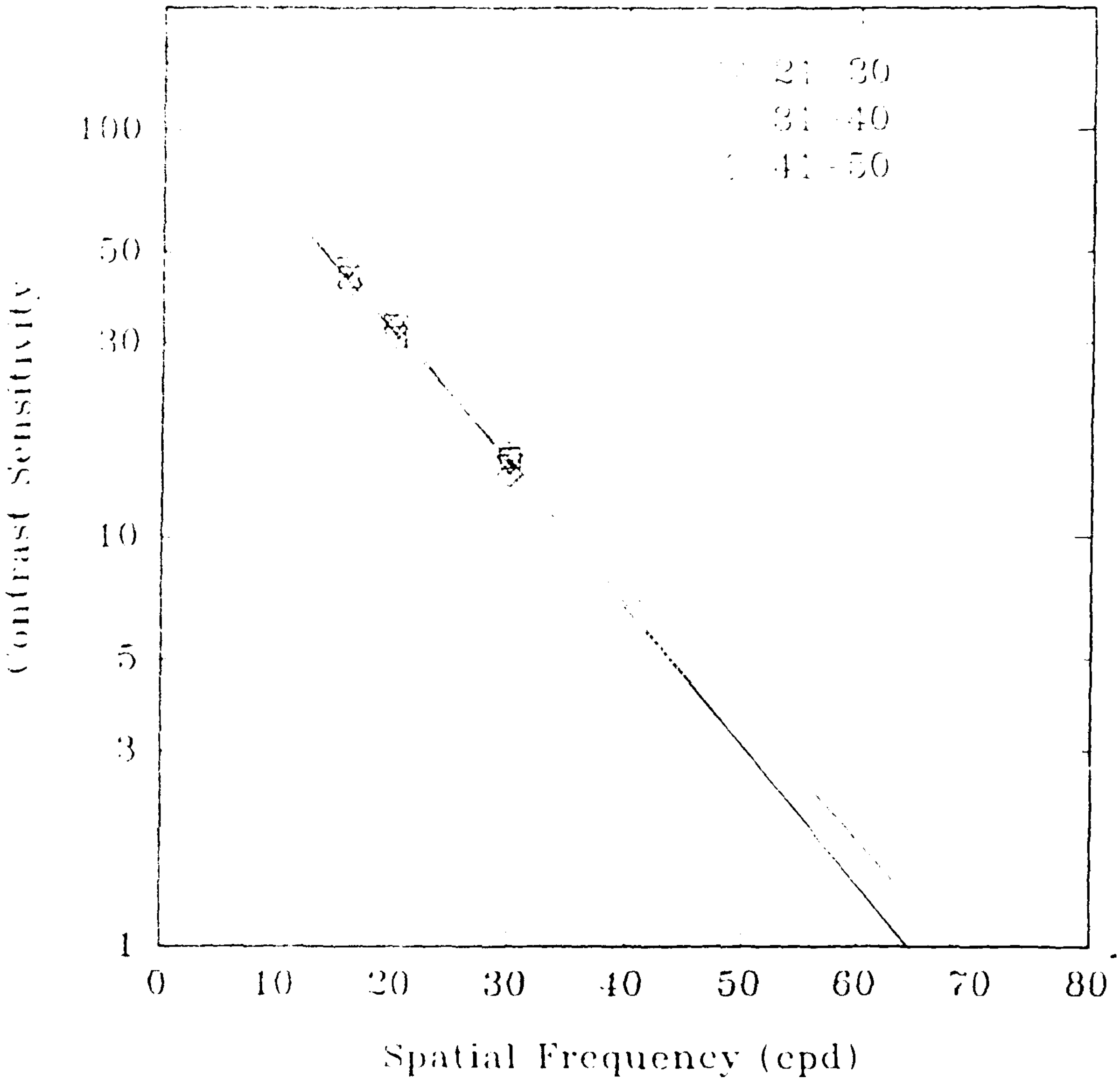

Figure 4. Contrast sensitivity (+1 sem) as a function of spatial frequency of interference gratings plotted log-linearly. The linear regressions for each of the 3 age groups are extrapolated to the axes. The X intercept gives the high spatial frequency cutoff. Note that these cutoffs based on the average contrast sensitivity will differ from the average cutoffs given in the section "Extrapolated High Frequency Cutoff."

Contrast Sensitivity to Gratings Without and With Glare

There was a significant difference between the contrast sensitivities across spatial frequency without and with glare ($F = 66$, $p<.00001$). The average contrast sensitivities across spatial frequency were 58 and 44 for the nonglare and glare conditions, respectively. Thus, apparent contrast sensitivity was about 25% (i.e., a decrease by .12 log units) less during glare than during nonglare. The contrast sensitivities to 4 and 12 cpd across age and glare conditions (52 and 50) were not significantly different ($F = 2.46$, $p = .12$). The contrast sensitivities across glare conditions and spatial frequencies did not vary significantly with age ($F = 1.3$, $p =.27$) (Fig. 5).

The interaction between age and glare conditions was not statistically significant ($F = .35$, $p = .71$). Thus, we could not reject the major null hypothesis that there are no significant differences in effects of glare as a function of age. The interaction between age and spatial frequency (across glare conditions) was not statistically significant ($F = 1.02$, $p = .36$). The interaction between age, glare condition, and spatial frequency was not statistically significant ($F = .16$, $p = .85$) (Fig. 5).

Increment Thresholds Without and With Glare

There was a significant difference between the Weber fraction without and with glare across age groups ($F = 185$, $p < .00001$). The average Weber fractions across age groups for nonglare and glare were 0.086 and 0.49 respectively. Thus, the apparent Weber fraction (and therefore the increment threshold) was about 5.7 times greater during glare than during nonglare (i.e., a change of .76 log units).

The major null hypothesis in this study involved the interaction between age and glare conditions. This interaction effect was significant ($F = 3.83$, $p = .025$). Increment thresholds during nonglare and glare for each age group were as follows:

Age Group I	0.083 and 0.466
Age Group II	0.083 and 0.4
Age Group III	0.093 and 0.61

The Weber fraction across nonglare/glare conditions varied significantly with age ($F = 3.94$, $p = .022$). Since the effect of age and the interaction between age and glare conditions were both significant, it was statistically justifiable to examine individual comparisons in posthoc tests. It was found that the Weber fraction did not vary significantly as a function of age during the non-glare condition ($F = .88$, $p =.42$). Thus, the simple age effect and the interaction effect were due to changes in the Weber

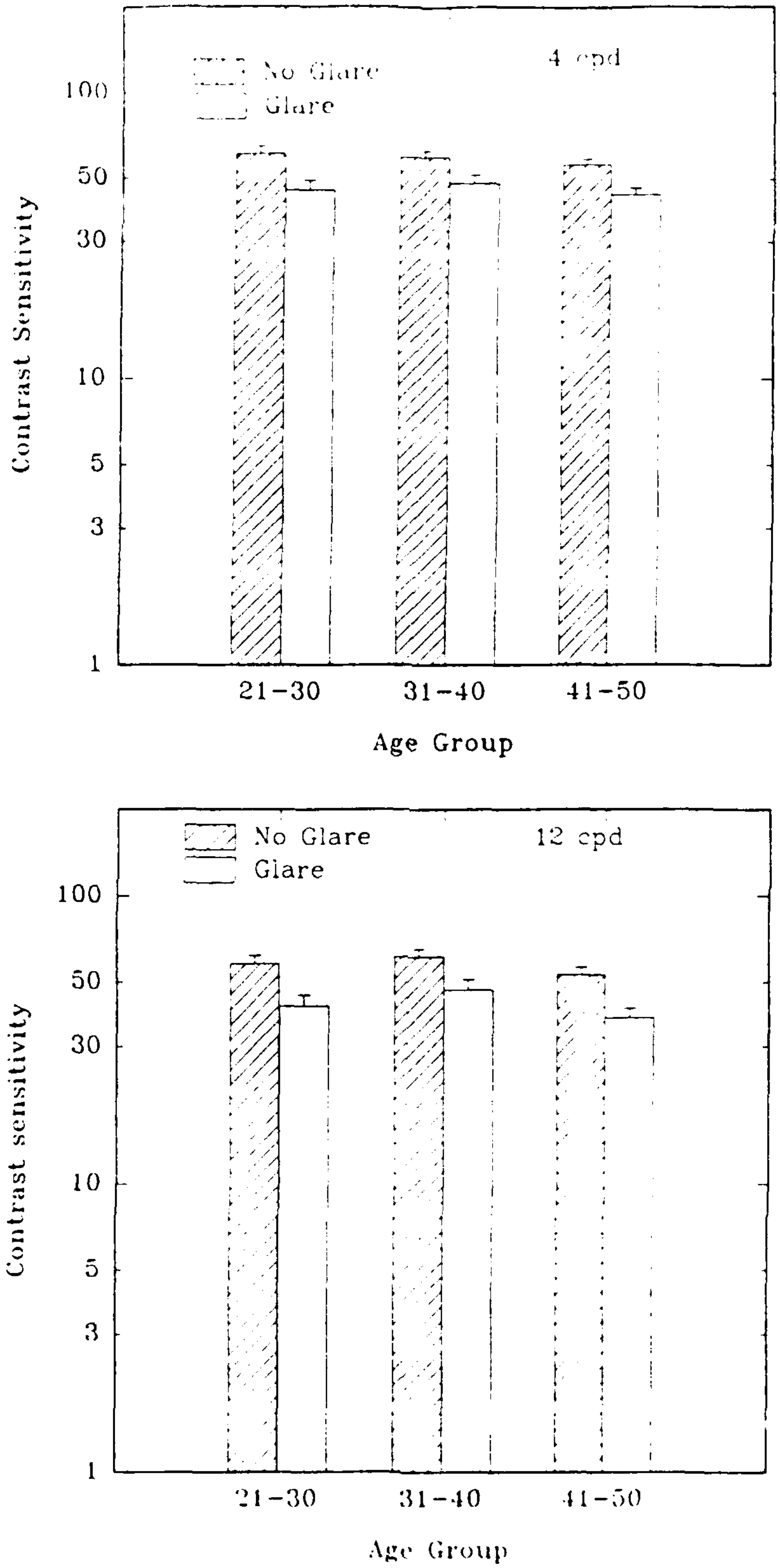

Figure 5. Contrast sensitivity to 4 cpd (top) and 12 cpd (bottom) without and with glare for the 3 age groups. The error bars indicate 1 standard error of the mean.

fraction during the glare condition. Posthoc analysis showed that the Weber fraction varied significantly as a function of age for the glare condition ($F = 3.92$, $p = .022$), but that this significant effect was fully accounted for by the significant difference between the Weber fraction during glare for Age Groups II and III ($F = 7.49$, $p = .0075$) and that there were no differences between Age Group I and II nor between Age Group I and III (Fig. 6). The average of the Weber fractions in Age Groups I and II differed significantly from that in Age Group III ($F = 7.12$, $p = .0089$). Therefore the best description of these results is that in the group over 40 years of age the Weber fraction during glare is significantly different from those in the 2 younger age groups.

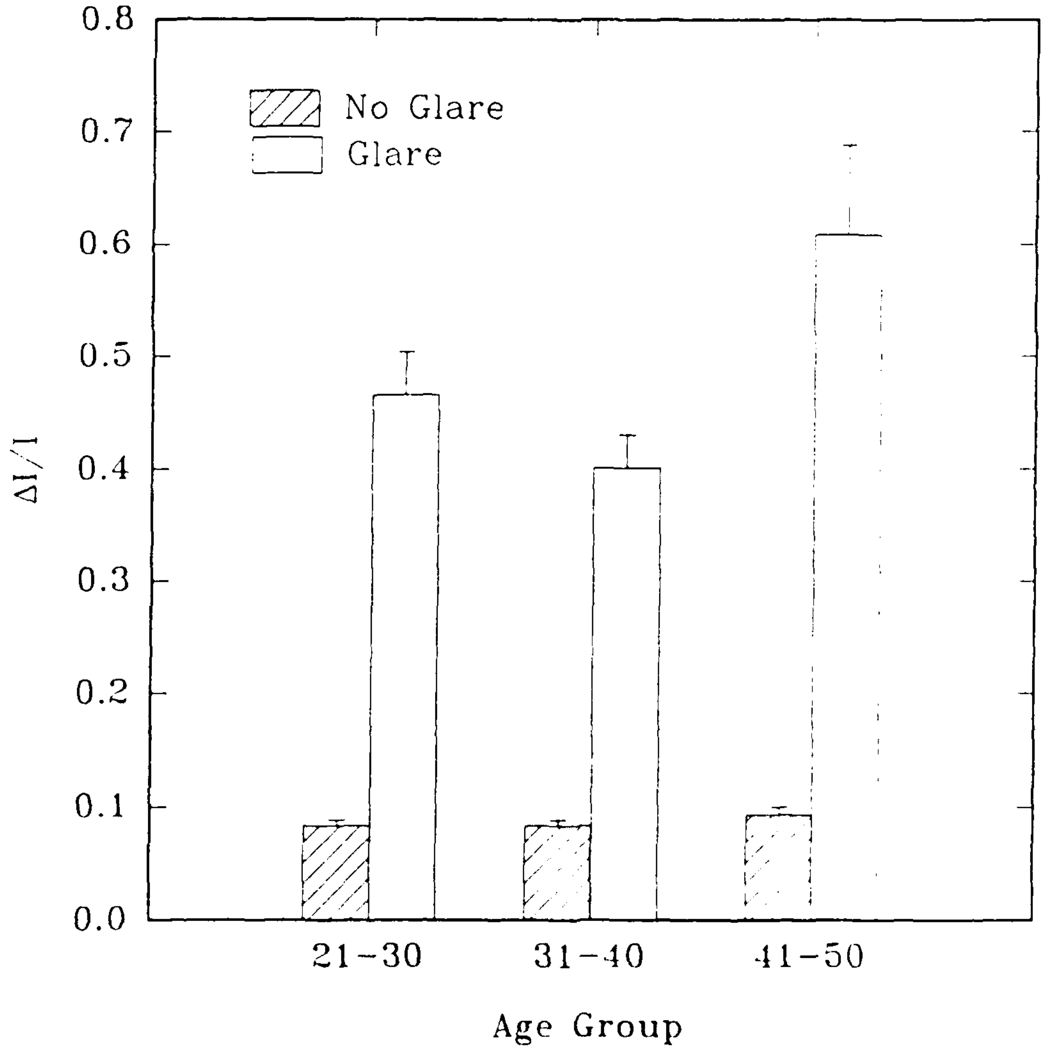

Figure 6. The Weber fraction without and with glare for each of the 3 age groups. One standard error of the mean is plotted in the positive direction.

Extrapolated High Spatial Frequency Cutoff

External Gratings

As mentioned earlier, the regression of the logarithm of the contrast sensitivities to 12, 16, and 20 cpd against the spatial frequency was determined for each subject and the high spatial frequency cutoff was determined. The cutoff spatial frequency did not vary significantly as a function of age ($F = .25$, $p = .78$). The mean cutoff spatial frequencies were 52, 55, and 54 cpd for Age Groups I, II, and III respectively. The average of these 3, 53.7 cpd, was quite close to the extrapolated cutoff based on the mean contrast sensitivities, 50 cpd. In comparing these results to the extrapolations in Figure 3, note that the data above are averaged cutoffs and not cutoffs based on average sensitivities as in the figure and that the two can differ. The same is true for the extrapolations of the interference grating data in the following section.

Interference Gratings

The high spatial frequency cutoff based on the interference grating data did not vary significantly as a function of age ($F = .11$, $p = .89$). The average cutoff frequencies were 77, 71, and 75 cpd for Age Groups I, II, and III, respectively (Fig. 4). The average cutoff frequency 74 cpd is larger than that based on the average interference grating contrast sensitivities, 66 cpd. The extrapolations based on the laser interference gratings contained many large outliers which contributed to the variability and to the very large mean. The cutoffs determined here agree closely with those determined by a linear regression to all of the data from two other experiments using the same device (34,42).

Pupil Diameter

We measured the pupil diameter for 55 of 90 subjects-20 subjects in Age Group I, 23 in Age Group II, and 12 in Age Group III. The pupil diameter did not vary significantly as a function of age ($F = .997$, $p = .38$). The pupil diameters produced by the 2° laser fringe target were: 5.82, 5.72, and 5.34 mm for Age Groups I, II, and III, respectively. There was a decrease in pupil diameter with age consistent with previous reports; however, the small differences seen in this study did not achieve significance and were much smaller than the 2 mm decrease over the same age range seen in the previous study (43). The small mean changes of pupil diameter and the lack of significance of the age-related change make it unlikely that pupil diameter can account for the changes or lack of changes

in contrast sensitivity with age or glare. Constriction during the glare exposure was considered to affect measurements by less than 10% (44) in previous studies of the equivalent luminance of glare sources.

DISCUSSION

A review of our past and present results and the relevant literature which were the basis of the present set of experiments prompted the following observations.

Examination of the Hypothesis and the Rationale for the Test

The motivation for the present study grew out of our demonstration (5,6) of a significant decrease in contrast sensitivity with age in normal subjects from 21 to 50 years of age. Hemenger's (20) theoretical model to explain the loss of contrast sensitivity with age incorporated contrast sensitivity and glare data from several different studies. The hypothetical physical basis of the model was age-related increase in narrow angle forward light scatter in the ocular media. His example included data from only 2 age groups, young (20- to 40-year-olds) and old (60- to 70-year-olds). However, it may not necessarily be true that differences in contrast sensitivity in the 2 age groups described above would have the same explanation as the gradual changes in contrast sensitivity in the 21- to 50-year-old group that we have postulated. Clinically detectable cataractous changes in the eye are much more common after the age of 50. Increase in optical density of the media starts to accelerate at about age 60 (45).

If age-related increased narrow angle light scattering due to subclinical changes in the ocular media in the 21- to 50-year-old group were the major cause of decreased contrast sensitivity, then this would be accompanied by an equivalent or greater increase in narrow angle glare susceptibility because of the known sensitivity of the glare technique to the presence of light scattering (35,37,38,39).

We have tested both contrast sensitivity (interference gratings and externally presented gratings) and glare susceptibility in the same large sample of subjects and we have simulated, in the 2 tests, nighttime and daytime glare. There have been several studies of the effects of aging on contrast sensitivity and on glare susceptibility. Many of the glare studies used stimuli with spatial frequency content less than 6 cpd and were contaminated by a confounding of simultaneous increase in brightness and contrast (e.g., those reviewed in Vos (21)).

Evidence for the Age-Related Loss of Contrast Sensitivity in the 21- to 50-Year-Old Group

Past Studies

An important premise in our reasoning is that contrast sensitivity decreases as a function of age in the 21- to 50-year-old group. Studies previous to ours (3) did not demonstrate significant changes in this age group, possibly due to small sample sizes (46). In our first study on binocular contrast sensitivity (6), we demonstrated a non-monotonic tendency towards significant differences between 66 Ss 21-30 years old and 37 Ss 31-40 years old with increasing spatial frequency. The difference reached the level of significance at 16 cpd. The differences for 20 and 24 cpd were slightly lower and were nearly but not significant. The variability of responses to 20 and 24 cpd was much greater possibly due to increased time necessary for arriving at threshold to higher spatial frequencies. The Kruskall-Wallis nonparametric statistic was used to test the difference because the data were not distributed normally; therefore, the other possible violations of the assumptions of the parametric tests about the distribution of variance and covariances were not relevant. There is a certain probability that 1 or more tests will be significant by chance alone when multiple tests are performed. There was no overall age or age-spatial frequency interaction and we were, therefore, not statistically justified in examining the individual spatial frequency-age interaction effects. The fact that the other high spatial frequencies were close to significance reinforced the notion that contrast sensitivity to high spatial frequencies tended to decrease with aging. This would be consistent with results from subjects over the age of 50 (3).

Monocular contrast sensitivity, in our second study (5), also varied with age in the 21- to 50-year-old age group. In the monocular study, subjects from age 21 to 40 years were pooled into one group and compared to subjects from age 41 to 50. In this study, contrast sensitivity was measured with the CRT, Vistech charts, and Regan slide tests. The effect of age on contrast sensitivity varied with the type of test. There was no overall significant age difference between the 2 age groups with the Vistech charts, but the age-spatial frequency interaction was significant justifying a search for the source of the significant interaction. For only 18 cpd, was there a significant difference between the 2 age groups. There was an overall difference between the 2 age groups for the Regan slide data. However, there was a significant age effect for the low contrast slide in which letters with maximum spatial frequency content of about 16-20 cpd could be detected. The interaction between age group and slide contrast was not significant. This means that there was about the same difference between the 2 age groups for detecting the letters in

the 3 slides. Because of the lack of significant age-contrast interaction, the examination of the individual comparison mentioned above was not justified.

Thus, the binocular CRT data and the monocular Vistech chart and Regan slide data were fairly consistent in showing a weak age-related decrease in contrast sensitivity to 16-18 cpd in the 20- to 50-year-old group despite significant difference in techniques and stimulus types in the 2 studies. However, there were some minor differences in the CRT contrast sensitivity in the binocular and monocular studies. There was an overall age group difference between monocular contrast sensitivities of the 2 age groups and a significant age-spatial frequency interaction. However, the contrast sensitivities to only 2 and 4 cpd differed significantly between the 2 age groups. This could be a difference due to the different division of the age groups in the 2 studies. This discrepancy is somewhat mitigated by the fact that the F values for 12 cpd approached significance ($p=.0532$).

Thus, the evidence for significant age-related changes in high spatial frequency sensitivity to gratings presented on a monitor was suggestive but mixed. The positive conclusions showing significant differences across age in the 21- to 40-year-old group were weak since the convention of not examining individual comparisons without an overall significant effect was violated. In the second, monocular study, there was an overall decrease in contrast sensitivity with age and an age-spatial frequency interaction, but only low and medium frequencies were involved in the significant interaction. Age-related changes in the light scatter of the media are not likely to affect low and middle spatial frequencies without a significant effect on high spatial frequencies.

The results with the Vistech charts were more robust. The contrast sensitivity to 18 cpd was greater for 21- to 40-year-olds than for 41- to 50-year-olds. Unfortunately, comparable results were not found in the CRT monitor data and the Regan slide data. This may be a result that occurs at random out the large number of tests that were performed. In addition, the sample sizes were not large and were not the same in the 2 groups.

Present Results

The present study revealed no significant age-related changes in contrast sensitivity in either the CRT or interference grating data for any spatial frequency investigated (4, 12, 16, and 20 cpd for the CRT; 16, 20, and 30 cpd for the interference gratings). This negative result is consistent with data from Owsley et al. (3), who did not have a sufficient sample size in this age range to make statistically powerful statements. They found no significant changes in contrast sensitivity in normal subjects until after the

age of 50. It is impossible to prove the null hypothesis, but the large number of subjects in the present study should allow a rather powerful statistical statement about the ability to detect a significant difference, if the magnitude of the change was 20% or more.

Analysis of the Glare Effect on Contrast Sensitivity and Increment Threshold

Effect on Perceived Target Diameter

The effect of glare on contrast sensitivity may not be a simple decrease in retinal contrast of the image of the target due to light scatter. First of all, light scatter on the retina over the retinal image of the target is not homogeneous (47), as is implied by the calculations of equivalent luminance (21). The intensity of the light scatter from a homogeneous annular surround would decrease towards the center of the target. Perceptually, what one sees is a smaller, lower contrast green target surrounded by a region of intense white light scatter in the target area, decreasing in intensity gradually in all meridians towards the center. The intense bright annular area obscures a variable target region depending on the subject. The scattered light obscuring the edges of the target effectively reduces the diameter of the target in addition to reducing the contrast of the remaining visible target area. Such an effect would be detected as a greater effect on lower spatial frequencies than higher because of the reduced number of cycles in the stimulus (48). This seemed to occur in the results of Abrahamsson and Sjostrand (38) although they attributed greater effect of glare on low spatial frequencies to a change of light adaptation level.

In our glare data there was no significant interaction betwee. spatial frequency and glare conditions. This implies that if effects due to decreased number of cycles or change in light adaptation level produced by the annular glare exist, they must be quite small. The interaction between spatial frequency, age, and glare condition was also not significant, thus making it less likely that the visible target cycles decrease significantly with age.

Effect of Glare on Level of Light Adaptation

It is possible that changes in sensitivity with increased light adaptation caused by the glare source could play a role in the glare effect. For young subjects, contrast sensitivity increases as a function of target luminance. The function relating contrast sensitivity to target luminance is different with older observers and is more accelerated, at least for middle spatial frequencies

(49). The curves of young and old observers eventually approach each other at high luminance. Much larger differences in contrast sensitivity between young and old are seen at low rather than high luminance. If such an effect were appreciable in the 21- to 50-year-old group, it could partially offset and thus mask an age-related increase in light scatter and the associated decreased externally measured contrast sensitivity. At the luminance level we have used, the differences between young and old are minimal and further changes with adaptation are small. Furthermore, the calculated equivalent luminance of the glare was only about 3.3 times the space average luminance of the display. Therefore the combined effective retinal illuminance would only be changed by a factor of a little more than 4 which would incur only small adaptational changes. Also, as mentioned earlier, there was no significant interaction of spatial frequency, glare, and age which would accompany such adaptation effects.

The effect of age on the curve relating increment threshold to background intensity has not been investigated. It is conceivable that, in the knee in the curve at the transition from mesopic to photopic levels of adaptation, the Weber fraction does not decrease so rapidly with increase of illumination for older observers. The equivalent luminance of the point glare source would cause such a change in adaptation level. The increased increment threshold during glare for the older observers may not be due to a greater equivalent luminance and therefore effective background intensity, but just to the fact that the scattered light due to the glare, although it is the same for old and young observers, may cause the increment threshold curve of the older observers to begin to rise with a steeper slope than that of the younger observers. There is a greater opportunity for confounding the results due to adaptational changes for the increment threshold study than for the CRT grating study simply because, proportionally, those changes are much greater at the mesopic photopic transition than in the middle to upper part of the photopic range.

Comparison of the Effects of Glare in the Increment Threshold and the CRT Grating Study

The glare effect demonstrated with the increment threshold apparatus was certainly robust. The threshold always increased during glare for every subject. This is an advantage since, without a glare effect in a normal population, it is difficult to interpret the lack of significant differences in glare effect in those pathological states in which you might want to investigate the possibility of increased glare susceptibility or scattered light. It may just be that if you increased equivalent luminance with greatly increased glare light, you might not cause a change in the glare test result in normals. If this were true, then this would not be a very sensitive glare test for conditions causing increased ocular light scatter.

A disadvantage of this glare test is that to achieve these large and replicable glare effects it is necessary to use a dim background level and very small eccentricity of the glare source. These factors make results with this apparatus susceptible to contamination because of inadvertent fixation of the glare source and because of confounding with possible adaptational changes. The point source makes the effects of glare easier to quantify, but the single bright point at a small eccentricity increases the likelihood of the subject fixating it.

The annular glare surround has the advantage of centering fixation on the target and decreasing the probability of direct fixation of the glare source. In this study, we chose to use a relatively high target brightness to simulate day vision and minimize rod contribution and draw upon the accumulated experience and database that we had at this brightness level. This entails the requirement of a very bright glare source, even at small eccentricities, to affect contrast sensitivity replicably. Additionally, for any given percentage change in the equivalent luminance due to increased light scatter, the contrast threshold will be affected by only one-half that percent. On average, there was a significant decrease in contrast sensitivity associated with the presence of the glare light. However, the glare effect would have been more unidirectional and and may have been less variable, had we used a lower target luminance.

The power to detect a significant difference if the glare had decreased contrast sensitivity 10% more for the older group than the younger group would have been high for this sample size. It is impossible to prove the null hypothesis, but it is unlikely that the effect of glare on contrast sensitivity is 10% greater or more for the older subjects in the 21- to 50-year-old group (i.e., that the equivalent luminance was 20% or more different). A lack of significant changes in susceptibility to glare has been demonstrated in more recent studies over even wider age ranges in some (2,50,51,52,53) even when there was an age-related decrease in contrast sensitivity (2,51,53).

The demonstration of a significant increase in increment threshold for Age Group III compared to Age Groups I and II only during the glare conditions complicates the interpretation for the increment threshold data. For Age Groups I and II, the interpretation is the same as described previously. The question is: Does the demonstrated significant increase in increment threshold during glare for Age Group III indicate an increased glare effect and hence ocular light scatter for the older age group? No similar effect was demonstrated in the contrast sensitivity data. Interference grating and CRT grating data maintained a constant ratio and neither decreased significantly as a function of age implying that that there is not likely to be a large age-related increase of light scatter or neural aging in similar subjects selected for ocular health in the age group from 21 to 50 years. The lack of a significant age-related increase in glare effect

agreed with this interpretation. The lack of a significant difference between the Weber ratio during glare for Age Groups I and III is also not fully consistent with an age-related increase in light scatter.

There are differences between the 2 paradigms which could possibly be the source of the discrepancy in the results:

1) The increment threshold-glare paradigm uses a point glare source while the CRT grating-glare paradigm uses an annular source.

2) The eccentricity of the increment threshold glare source is less than that of the CRT grating source.

3) The increment threshold target diameter is less than that of the CRT target.

4) The increment threshold technique is more susceptible to contamination due to adaptation changes associated with the glare light than the contrast sensitivity technique.

A significant increase in light scatter would not only be associated with an increased threshold during glare but also during nonglare. The significant increase in threshold during only the glare condition for Age Group III is paradoxical relative to the scattered light hypothesis.

Equivalent Luminance of the Glare Source as a Function of Age

Vos (21) has thoroughly reviewed the literature on disability glare and the change of disability glare with age. He has combined data from his own laboratory with that of others to describe the effect of glare at eccentricities from 0 to 100° from ages 20 and up. His resulting mathematical expression of these effects agrees closely with that of other investigators in their eccentricity domains of validity. The expression is as follows:

$$f(\theta) = \frac{10 + (5 \times 10^{-7} \times A^4)}{(\theta + .02)^2} + \frac{10}{(\theta + .02)^3} \qquad (1)$$

A = Age of subject

θ = Eccentricity of small area glare source (deg)

Expression from Vos, 1984

Padmos (54) has derived the mathematical expression for calculating the equivalent luminance of an extended annular glare source.

$$L_{eq} = \left(\frac{(2\pi)^2}{360} \int_{\theta_1}^{\theta_2} f(\theta) \sin\theta \, d\theta\right) L_{eg} \qquad (2)$$

L_{eq} = Equivalent veiling luminance (cd/m^2)

L_{eg} = Luminance of the extended glare source (cd/m^2)

$\theta_{1,2}$ = Inner and outer diameters of annular glare source (deg)

Using the Padmos formulation, with the age-correction in the Vos formula, we have calculated the equivalent luminances for the average ages in Age Groups I and III. At 26.1 years of age, which was the average in Age Group I, the calculated equivalent luminance was 228 cd/m^2. The empirical equivalent luminance calculated using the formula of Abrahamsson and Sjostrand (38):

$$L_{eq} = L_{mean}(1.2(C_g/C_n)-1) \qquad (3)$$

where: L_{mean} = spaced average luminance of the display
C_g = contrast during glare
C_n = contrast without glare

was 41.9 cd/m^2. Thus, there is a very large discrepancy between the value predicted by the Vos formula and the value determined empirically by the ratio between contrast with and without glare. Our demonstrated small effect on the contrast sensitivity compared to the effect predicted by the Vos expression agrees with the qualitative descriptions of others who have used this technique (37,38). Unfortunately, these authors present quantitative data on only 2 normal subjects. The reason for this discrepancy between predicted and observed values is unclear. The Vos formula, however, is based on increment threshold data with spots of light without narrow band spatial frequency content. The distribution of optically scattered light on the retina is not isotropic. The convolution of the 2-dimensional profile of the scattered light retinal illuminance with the grating retinal illuminance may result in effectively higher integrated contrast during glare than that for the flashing spot.

The calculated equivalent luminance for Age Group III (45.5 years average age) was 250 cd/m^2, an increase of about 10%. A change of this magnitude may not be detectable given the power of our technique. However, some authors (quoted in Vos 21) predict much larger age effects in this age range. One purpose of this study was to estimate the age-related change in light scatter as measured

indirectly by equivalent luminance. The empirical equivalent luminance determined by the method of Abrahmsson and Sjostrand was 36.3 cd/m^2, a 13% decrease in empirically determined equivalent luminance. This change is in the opposite direction from that predicted by the hypothesis of age-related increase in ocular light scatter.

Glare did not cause a decrease in contrast sensitivity to the gratings for all subjects. For some subjects, the contrast sensitivity actually increased during the glare condition (Figs. 7, 8, and 9). This occurred in about 10% of the Ss in the 3 age groups. There was no systematic relationship between person or age and the occurrence of this phenomenon; thus it would not affect our conclusions on the change of light scatter with age. We asked several subjects who had higher contrast sensitivity during the glare condition if they could tell that they could see the stimulus more easily during glare. They said that it was easier to detect the stimulus during the glare condition and that the presence of the glare source seemed to make the task easier to perform by providing a centering reference. The increase in contrast sensitivity might be due to idiosyncratic changes in pupil diameter in these subjects at these times. The increase in contrast sensitivity in those cases may also be due to sampling error and there may, in fact, have been no difference between the glare and nonglare conditions. However, with an equivalent luminance this high, there should be a large enough glare effect to detect with our techniques.

One certain conclusion is that the annular glare source for the grating experiment was not intense enough to produce a replicable glare effect with all subjects. The glare effect varied from a change of -20% to 50% depending upon age and spatial frequency. It has been demonstrated that the glare model breaks down as the glare luminance decreases (47). The equivalent luminance at which this occurs is .33 to .5 times the stimulus luminance, depending on age. The calculated equivalent luminance of the glare source in this study was 3.3 times the space averaged stimulus luminance which is high enough for applicability of the formulae describing equivalent luminance.

For the increment threshold data, the calculated equivalent luminance for the young group was 4.24 cd/m^2. Applegate et al. (35) had an empirical value for the equivalent luminance of 2.4 cd/m^2. The age of the subjects in the Applegate et al. study was not specified. The empirical equivalent luminance in our study, determined using the Weber function from the young normals in the Applegate et al. study,

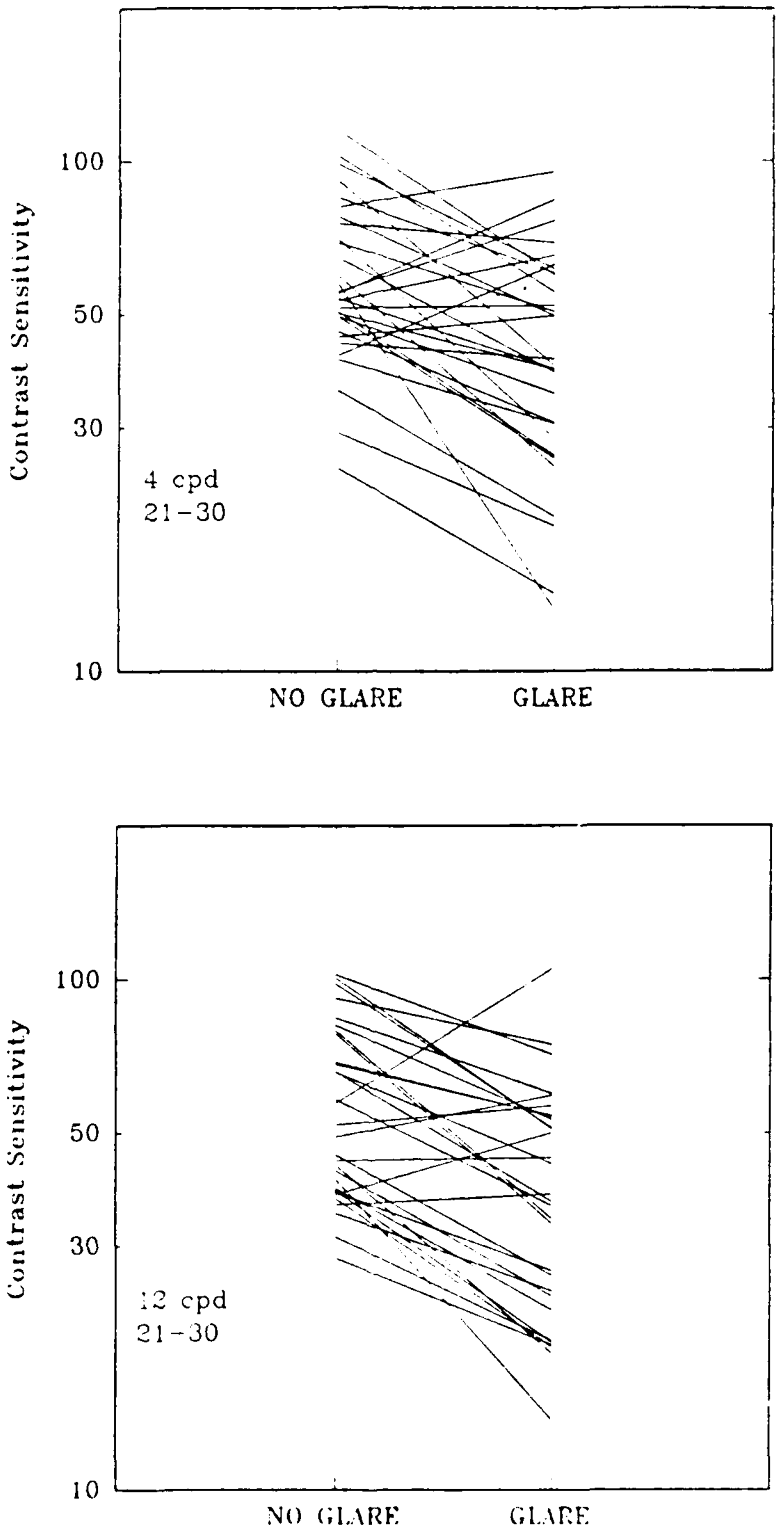

Figure 7. Contrast sensitivity for each subject in the 21-30 age group without and with glare for 4 (top panel) and 12 cpd (bottom panel).

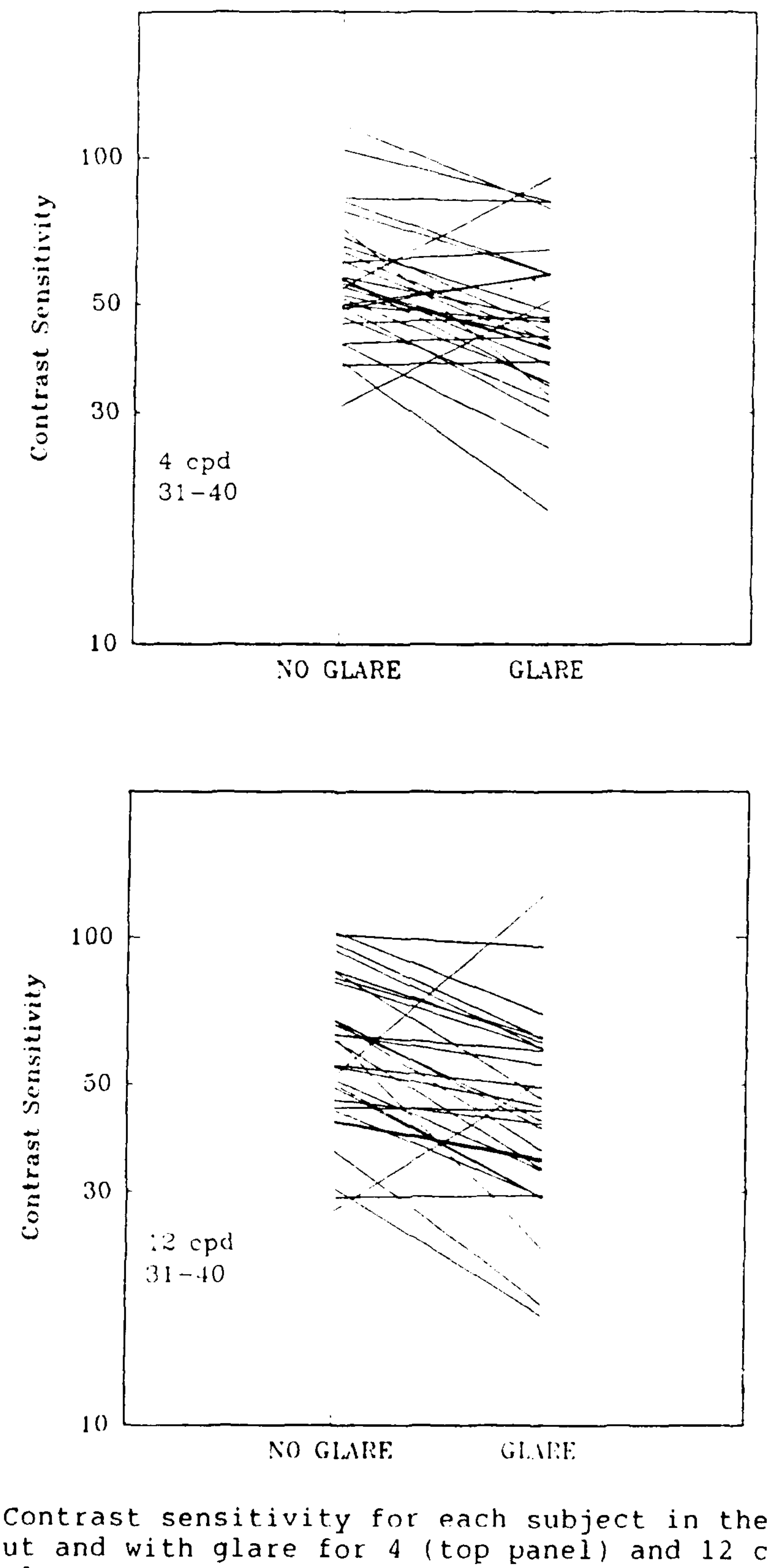

Figure 8. Contrast sensitivity for each subject in the 31-40 age group without and with glare for 4 (top panel) and 12 cpd (bottom panel).

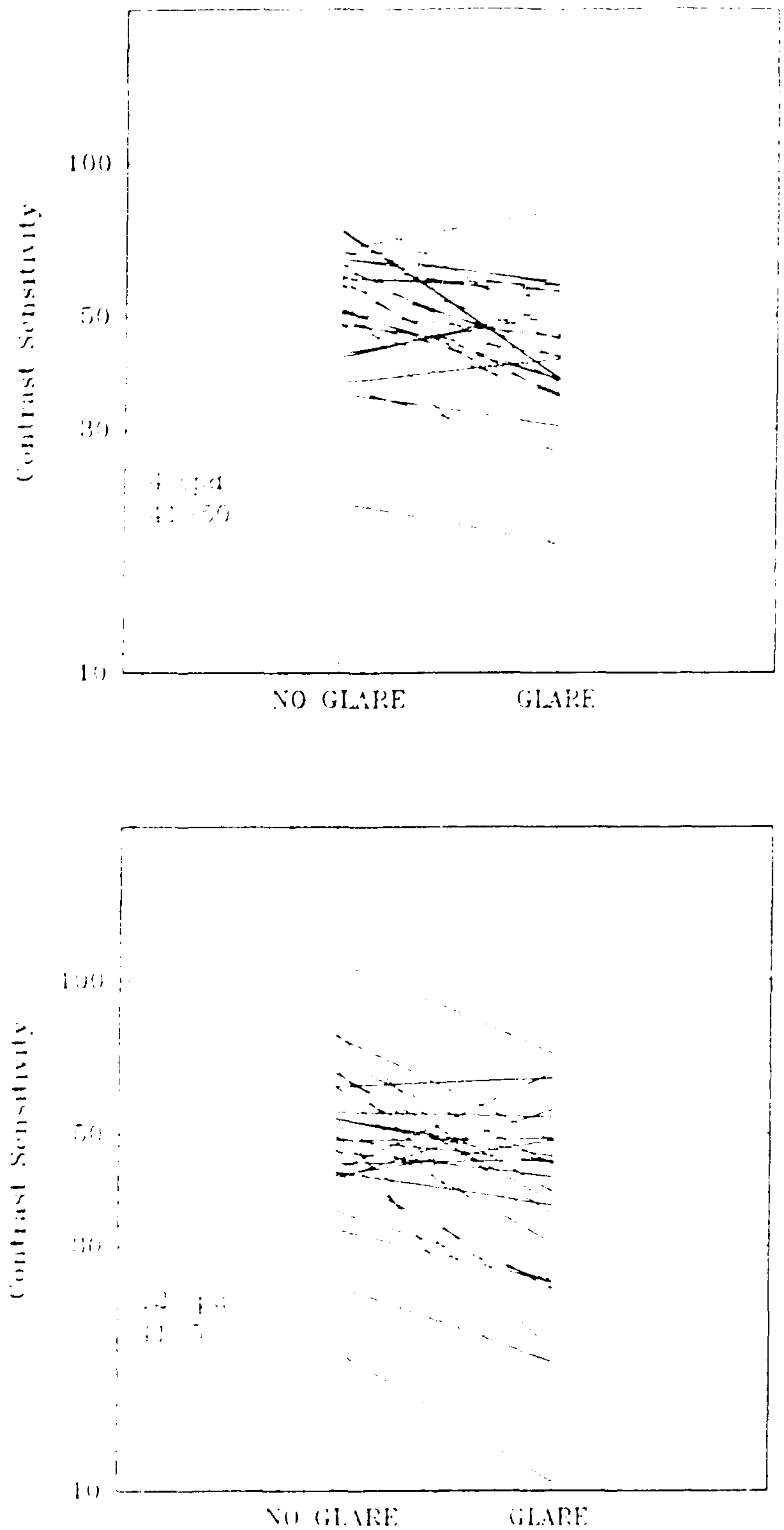

Figure 9. Contrast sensitivity for each subject in the 41-50 age group without and with glare for 4 (top panel) and 12 cpd (bottom panel).

was 4.5 cd/m^2 in the young age group. In the oldest age group (average age 45.5), it was 6.6 cd/m^2 which was an increase by a factor of 1.47. The Weber fraction during the nonglare and glare conditions (.08) for the young group was within 1 standard deviation of that of the Applegate et al. study for the non-glare condition (.06). The value during glare in our study (.47) exceeded 2.5 standard deviations from the mean in the Applegate et al. study (.21). Thus, there was no difference in the 2 studies without glare, but the threshold during glare in our study was significantly higher than that during glare in the Applegate et al. study. The Vos model underpredicts the equivalent luminance of the young age group by only about 6%. This is much closer agreement than for the CRT grating-glare experiment. However, for the older age group, the correspondence was not so close. The predicted equivalent luminance was 4.6 cd/m^2 compared to the obtained value of 6.6 cd/m^2. This discrepancy is still much less than that with the grating data. This closer correspondence is not surprising given that the Vos formula was based on increment threshold data and not contrast sensitivity to gratings.

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